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August 8, 2005

American Society for Precision Engineering 2005 Annual
Meeting
Norfolk, VA, United States
October 9, 2005 through October 14, 2005

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System Dynamics and Control System for a High Bandwidth Rotary Actuator and Fast Tool Servo

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Keywords: short-stroke rotary actuator, high bandwidth, fast tool servo, diamond turning, textured surface, magnetic suspension

Introduction

This paper explores some of the system dynamics and control issues for a short-stroke rotary actuator that we designed and tested for a new fast tool servo referred to as the 10 kHz rotary fast tool servo. The use of a fast tool servo (FTS) with a diamond turning machine for producing non-axisymmetric or textured surfaces on a workpiece is well known. In a previous paper [1] the authors provide details on the mechanical design and trade-off issues that were considered during the design phase for the fast tool servo. At the heart of that machine is the normal-stress variable reluctance rotary actuator described in more detail in this paper. In addition to producing the torque that is needed for the 10 kHz rotary fast tool servo, the actuator produces a force and is therefore referred to as a hybrid rotary/linear actuator.

The actuator uses bias and steering magnetic fluxes for linearizing the torque versus current relationship. Certain types of electric engraving heads use an actuator similar in principle to our hybrid actuator. In the case of the engraving heads, the actuator is used to produce and sustain a resonating mechanical oscillator. This is in sharp contrast to the arbitrary trajectory point-to-point closed-loop control of the tool tip that we demonstrate with our actuator and the 10 kHz FTS. Furthermore, we demonstrate closed-loop control of both the rotary and linear degrees of freedom for our actuator.

We provide a brief summary of the demonstrated performance of the 10 kHz rotary fast tool servo, and discuss the magnetic circuit for the actuator and some of the related control issues. Montesanti [2] provides a more detailed and thorough discussion on the 10 kHz rotary fast tool servo, the hybrid actuator, and the pertinent prior art.

The 10 kHz Rotary Fast Tool Servo

Figure 1 shows the 10 kHz rotary fast tool servo mounted on a diamond turning machine and engaging a workpiece. The rotor for the fast tool servo and its flexure bearing are also shown in Figure 1. The rotor consists of the moving element of the actuator and the tool holder that is directly attached to it. The 10 kHz rotary fast tool servo has a demonstrated closed-loop sinusoidal tool stroke of 70 μm PP at low frequencies and 8.0 μm PP at 5 kHz

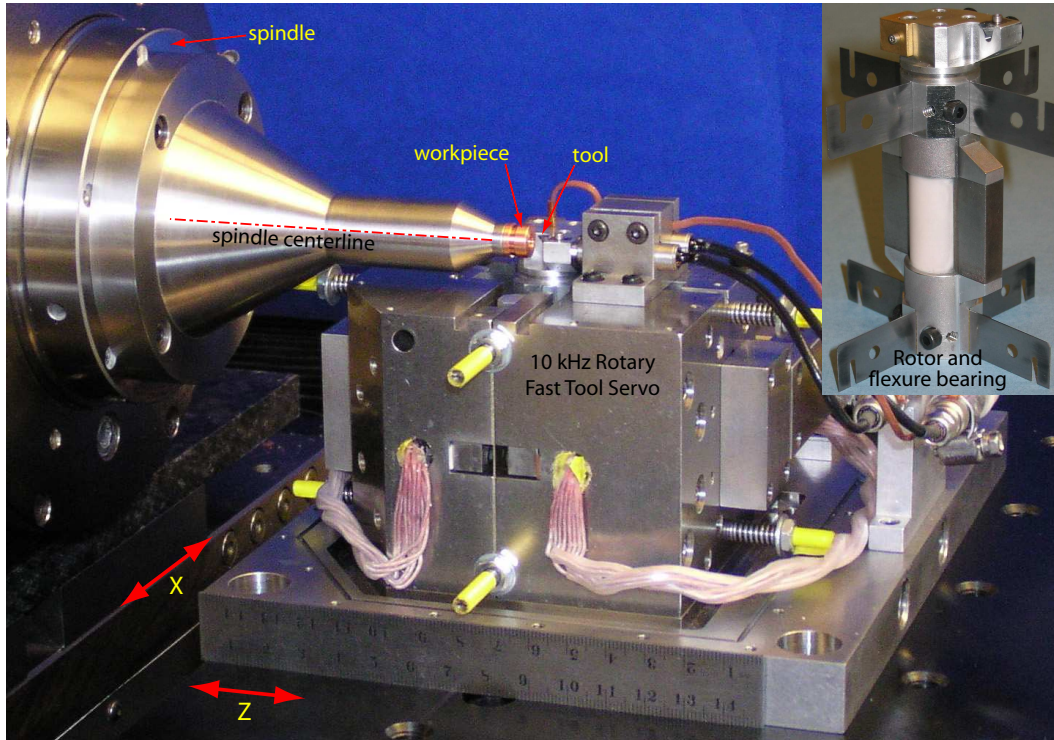


Figure 1: The 10 kHz rotary fast tool servo on a diamond turning machine, and the rotor for the fast tool servo with its flexure bearing (inset).

(400 g tool tip acceleration). With the aid of a stable mechanical resonance at 10 kHz that stores and recovers energy supplied by the actuator we demonstrated a closed-loop sinusoidal tool stroke of $4.2 \mu\text{m}$ PP at 10 kHz with this machine (870 g tool tip acceleration). The tool position noise level is 1.4 to 2.5 nm rms, depending on the magnitude of the bias flux being used. The measured small-signal closed-loop response for the tool position has a -3dB bandwidth of 10 kHz. The closed-loop magnitude and phase angle are fairly smooth curves up to 5 kHz, suggesting that a possible future addition of a feedforward compensator would be effective for achieving precise tool tip trajectories up to that frequency.

Hybrid Rotary/Linear Actuator

Figure 2 shows a model of the magnetic circuit for the actuator. The rotor core is a rectangular prism suspended between two opposing C-shaped stator cores with nominal air gaps of $50 \mu\text{m}$ at the four pole faces. The rotor and stator cores are made of laminated soft magnetic material to reduce the hysteretic and eddy current losses associated with the AC steering flux. A DC coil provides a biasing magnetic flux in the four air gaps. Each stator core with its two AC coils forms a magnetic circuit with the rotor core. Considering one of the stator cores, energizing its AC coils in a manner that produces flux in a common direction creates a steering flux that circulates around that stator core and the rotor core via the two air gaps between the two. The bias and steering fluxes add at one of those gaps and subtract at the other. The same thing occurs between the other stator core and the rotor core. With proper

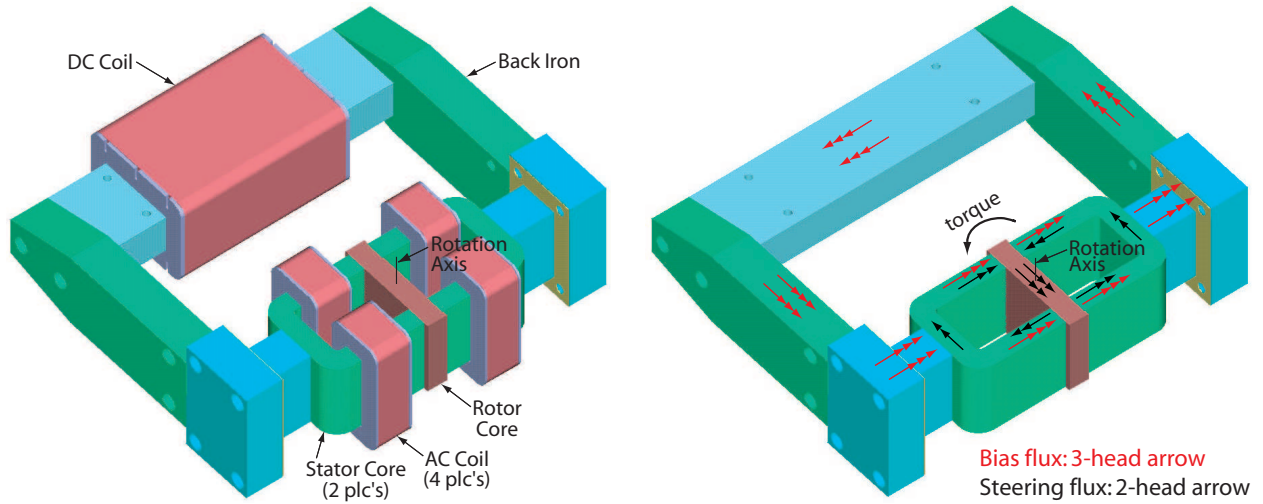


Figure 2: Model of the magnetic circuit for the hybrid actuator (left). Coils removed to show flux lines (right).

phasing of the AC fluxes in the two stator cores and balanced magnitudes of DC and AC fluxes, the fluxes can be made to add in diagonally opposed air gaps and subtract in the opposite diagonally opposed air gaps, resulting in a net torque on the rotor with nominally no net force on it. The DC magnetic bias linearizes the relationship between the torque and steering-coil currents, which makes controlling the actuator a straight-forward task.

The bias flux causes the rotary mode of the actuator to be open-loop unstable. Referring to Figure 3, if the steering fluxes are set to zero and the rotor is displaced clockwise, then the bias flux will preferentially flow through stator poles 2 and 4 and cause the rotor to turn until it makes contact with those stator poles. Adding the torque-generating steering flux depicted by the double-head arrows in Figure 3 counteracts this effect. By adding a sensor for measuring the rotation, and a control system, this rotary mode is controllable and we have a rotary actuator.

A permanent magnet can be used instead of the current-carrying coil shown in Figure 3 to produce the bias flux. We found it advantageous to use a coil because it allowed us to adjust the magnitude of bias flux during testing of the actuator. Note that the air gaps between the stator cores and the back-iron (the portion carrying the bias coil) are needed to magnetically decouple the two stator cores when a bias coil is used instead of a permanent magnet.

In addition to the bias flux and torque generating fluxes that were shown in Figure 2, Figure 3 includes the force generating fluxes depicted by the single-head arrows. There are two ways to generate a radial force in the Z-direction on the rotor. The first is as shown in Figure 3 for the case when the rotor is centered between the two stator halves and the two torque-producing steering currents i_{12T} and i_{34T} are nominally equal. In this case, a net force in the positive Z-direction is produced by increasing the steering coil current for the left stator half to $i_{12} = (i_{12T} + i_{12F})$, and decreasing the steering coil current for the right stator half to $i_{34} = (i_{34T} - i_{34F})$. The second way to generate a force is for the case when the rotor is slightly closer to one of the stator halves and there are equal steering coil currents

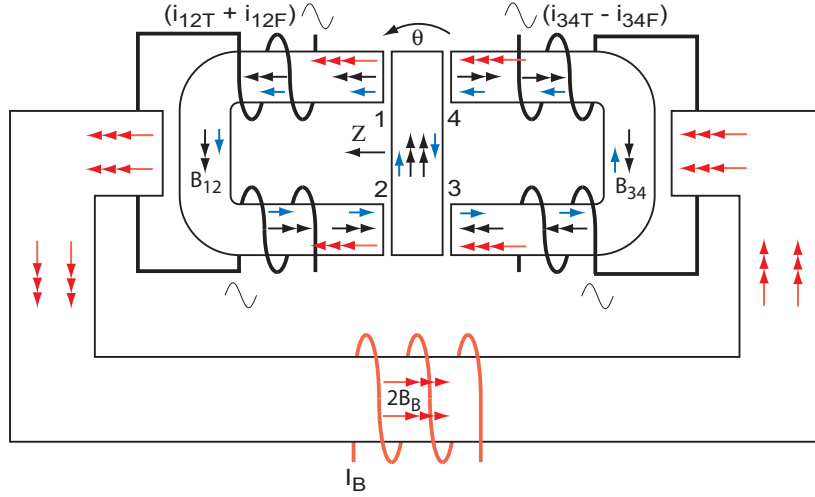


Figure 3: Sketch of the magnetic circuit for the actuator.

for both stator halves. For example, if the rotor was initially closer to the right stator half, then the force generating fluxes shown in Figure 3 would cause the rotor to move to the left. By adding a sensor for measuring the Z-direction displacement, and a control system, this linear mode is controllable and we have a linear magnetic suspension.

For the magnetic circuit shown in Figure 3, torque control is independent of force control, but force control requires a torque-generating current to act as an operating point. We demonstrate closed-loop control of the torque mode and of the force mode for the hybrid actuator that we built for the 10 kHz rotary fast tool servo, and use the force mode to provide electronic damping. A discussion on alternate magnetic circuits having fully decoupled rotary and linear modes, and suggested future work that utilizes the force mode as an active suspension for improving the performance of a predominantly rotary system, is provided by Montesanti in [2].

Acknowledgements

In accomplishing this work, we acknowledge helpful discussions with Professors James Kirtley, Samir Nayfeh, and James Roberge at MIT, and our colleagues in the Precision Motion Control Laboratory at MIT.

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References

- [1] R.C. Montesanti and D.L. Trumper. A 10 kHz Short-Stroke Rotary Fast Tool Servo. In *Proceedings of the American Society for Precision Engineering 2004 Annual Meeting*, 34 (2004): 44–47.
- [2] Richard Clement Montesanti. *High Bandwidth Rotary Fast Tool Servos and a Hybrid Rotary/Linear Electromagnetic Actuator*. PhD thesis, Massachusetts Institute of Technology, September 2005.